Predicting postfire mortality of seven western conifers

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We used data on 2356 trees from 43 prescribed fires in Idaho, Montana, Oregon, and Washington states to model postfire tree mortality. Data were combined for seven species of conifers to develop binary logistic regression models for predicting the probability of mortality. Probability of mortality increased with percentage of the crown killed, and decreased as bark thickness increased. Models are presented with and without species as a categorical variable. The models predicted well for trees burned in both slash fires and fires in natural fuels. The models are applicable for assessing fire-caused mortality both of individual trees and in mixed conifer stands of the Pacific Northwest.

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Les données provenant de 2356 arbres dans 43 brûlages contrôlés effectués dans les États de l'Idaho, du Montana, d'Orégon et de Washington ont servi à modéliser la mortalité des arbres après le brûlage. Les données relatives à sept espèces de conifères ont été amalgamées pour permettre l'élaboration de modèles logistiques binaires de régression dans le but de prédire la probabilité de la mortalité. Cette probabilité augmentait à mesure qu'augmentait la proportion de la cime morte et diminuait avec l'augmentation de l'épaisseur de l'écorce. Les modèles sont présentés avec et sans l'emploi des espèces de conifères comme variables catégoriques. Ces modèles offrent de bonnes prédictions pour les arbres qui ont brûlé soit dans des incendies de débris de coupe, soit dans ceux alimentés par des combustibles naturels. Ces modèles sont en outre applicables à l'évaluation de la mortalité attribuable au feu aussi bien pour les arbres individuels que pour les peuplements mélangés de conifères de la région du Pacific Northwest.

[Traduit par la revue]

Introduction

Managers need the ability to predict fire-caused tree mortality to use prescribed fire effectively and to plan postfire management following prescribed fires and wildfires. The objective of this study was to develop a method for predicting postfire mortality of seven western conifer species, given morphological measurements that are readily available to managers.

Coniferous species in the northwestern United States vary widely in their resistance to fire injury. Trees of similar size and age but of different species may vary considerably in the amount of injury from the same exposure to fire. This observation has led to the ranking of species as more or less resistant on the basis of morphological characteristics such as crown development, bark thickness, and rooting depth (Brown and Davis 1973; Minore 1979).

Crown characteristics, including the height of the crown above the ground, foliage density, and bud size, affect a tree's resistance to injury from fire. Although resistance to crown injury varies because of these characteristics, there is no conclusive evidence that the likelihood of mortality differs between trees with the same relative level of crown injury. The best indicator of crown injury appears to be the proportion of the crown (foliage and buds) scorched or killed (Ryan 1982; Ryan et al. 1988; Peterson 1985). Numerous studies have shown that little mortality results from light crown injury alone. The probability of mortality increases as crown injury progresses to higher levels and approaches 1 when all of the crown is killed (Mitchell and Martin 1980; Ryan 1982).

Resistance to cambium injury from similar fires theoretically varies directly with the square of the thickness of the insulating bark layer (Martin 1963; Reifsnyder et al. 1967). Field studies (Hare 1965; Vines 1968) have confirmed this

theory. Morphological characteristics (de Ronde 1982; Harmon 1984) and thermal properties (Riefsnyder et al. 1967) of bark vary with species, affecting resistance to cambium injury, but these factors are thought to be less important than differences in bark thickness (Martin 1963; Brown and Davis 1973; Ryan 1982). Although cambium injury is known to vary with bark thickness, its contribution to tree mortality is poorly understood. Ryan et al. (1988) found that cambium injury resulting from low-intensity prescribed fires in Douglas-fir was a stronger predictor of mortality than crown scorch.

In the coniferous forests of the northwest the various characteristics affecting resistance to fire injury tend not to be independent. For example, the shallow-rooted conifers tend also to have thin bark, making them highly susceptible to injury from surface fires. Conversely, deeper-rooted species tend to have thicker bark and are relatively resistant to fire injury (Minore 1979). Younger trees tend to have both thinner bark and crowns nearer the flame zone. Thus, some trees are more susceptible to multiple injuries.

Interactions between fire-caused injuries undoubtedly affect postfire mortality. For example, it is widely held that mortality increases when crown injury is accompanied by cambium injury (Herman 1954; Wagener 1961). Partial basal girdling in the absence of crown injury does not appear to seriously affect survival (Kramer and Kozlowski 1979). Mortality due to complete girdling does occur, however, particularly when thin-barked trees are burned by light surface or smoldering ground fires. Trees with very thin bark will succumb to virtually any fire vigorous enough to encircle them.

For modeling purposes we assume that over a wide range of conditions, trees respond similarly to a given level of fire injury and that the primary difference in the observed mortality of different species and age-classes stems from dif-

TABLE 1. Description of tree mortality data sets

Data set	Region 1	Lubrecht	West Cascades	Coram
No. of fires	9	20	13	1
No. of trees	348	422	798	788
Plot size (ha)	6–9	0.12	0.7	9
Average fireline intensity (kW/m)	630–2200	100–900	720–2350	850
Fuel model[a]	J,K	H	J,K	J
10-h fuel moisture content (%)[a]	8–15	5–15	6–25	9
1000-h fuel moisture content (%)[a]	16–26	11–27	11–30	24
Species[b]	DF,WL,ES,LP,SF	DF,WL,LP	DF,RC,WH	DF,WL,LP,SF

[a]According to national fire danger rating system (NFDRS) (Deeming et al. 1977).
[b]DF, Douglas-fir; WL, western larch; ES, Engelmann spruce; LP, lodgepole pine; SF, subalpine fir; RC, we

▲ WEST CASCADES
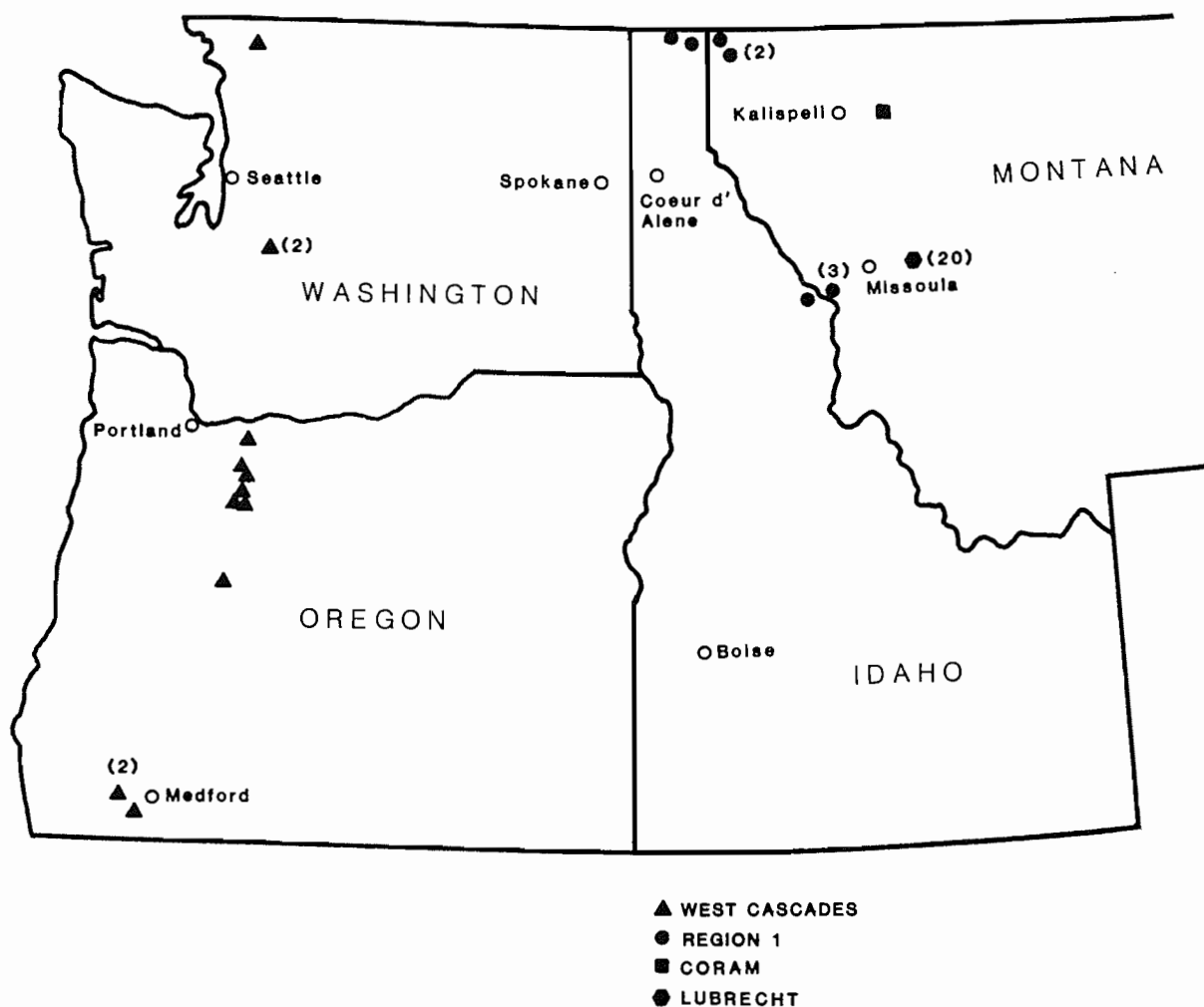● REGION 1
■ CORAM
⬤ LUBRECHT

FIG. 1. Location of 43 prescribed burning study sites.

ferences in injuries received. Because the actual injuries sustained by a tree in a given fire should be proportional to its resistances, morphological characteristics can be used to predict mortality in lieu of actual injury measurements. We assumed that resistance to cambium injury varied with bark thickness. Bark thickness and percentage of the prefire crown killed were used as independent variables in the prediction of mortality.

Methods

Data from separate studies on four experimental plots (west Cascades, Region 1, Coram, and Lubrecht) were pooled for analysis, providing information on 2356 trees from 43 prescribed fires in Idaho, Montana, Oregon, and Washington (Table 1, Fig. 1).

The combined data set provided information on fire-caused mortality of seven conifer species over a range of tree sizes and fire injuries (Table 2). Species included in the study are Douglas-fir

TABLE 2. Data for seven species of fire-injured trees

	Tree height (m)			DBH			BT (cm)			Scorch height (m)			% CK		
	$\bar{x}$	SD	Range	$\bar{x}$	SD	Range	$\bar{x}$	SD	Range	$\bar{x}$	SD	Range	$\bar{x}$	SD	Range
Douglas-fir ($n = 1488$)	26.1	12.7	6–68	41.3	24.0	8–166	2.68	1.56	0.5–10.8	13.0	8.8	0–42	10.6	24.1	0–100
Western larch ($n = 287$)	28.5	8.2	11–43	43.3	17.3	13–90	2.61	1.09	0.7–5.5	13.6	5.4	0–33	15.1	23.9	0–95
Engelmann spruce ($n = 96$)	27.1	10.5	7–45	44.0	18.0	13–95	1.16	0.40	0.5–2.3	6.9	4.6	0–19	32.2	36.1	0–99
Lodgepole pine ($n = 144$)	19.9	6.2	7–39	25.2	8.6	13–53	0.43	0.12	0.3–0.8	10.3	4.8	0–25	35.3	37.3	0–100
Subalpine fir ($n = 172$)	17.8	4.1	6–30	23.9	4.5	10–41	0.36	0.07	0.2–0.6	5.8	3.1	0–16	5.3	16.5	0–90
Western red cedar ($n = 69$)	21.5	9.3	7–43	36.3	17.9	13–89	1.15	0.37	0.7–2.3	7.7	6.6	0–29	71.0	35.0	0–100
Western hemlock ($n = 100$)	16.1	7.2	7–37	23.2	10.1	13–69	1.05	0.44	0.6–3.0	5.8	2.6	1–14	60.2	38.3	0–100

NOTE: BT, computed bark thickness; % CK, percent crown kill.

TABLE 3. Single bark thickness (BT) as a function of diameter outside bark (DOB) for seven western North American conifer species

	Equation (cm)	Source
Douglas-fir	BT = 0.065 DOB	Monserud 1979
Western larch	BT = −0.1143 + 0.0629 DOB	Faurot 1977
Engelmann spruce	BT = 0.189 + 0.022 DOB	Smith and Kozak 1967
Lodgepole pine	BT = 0.0688 + 0.0143 DOB	Faurot 1977
Subalpine fir	BT = 0.015 DOB	Finch 1948
Western red cedar	BT = 0.386 + 0.021 DOB	Smith and Kozak 1967
Western hemlock	BT = 0.056 + 0.043 DOB	Smith and Kozak 1967

(*Pseudotsuga menziesii* (Mirb.) Franco), western larch (*Larix occidentalis* Nutt.), Engelmann spruce (*Picea engelmannii* Parry), lodgepole pine (*Pinus contorta* Dougl.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), western red cedar (*Thuja plicata* Donn), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Species, diameter at breast height (DBH), tree height, scorch height, and visual estimates of the percentage of the prefire crown (foliage and bud) volume killed by the fire were recorded in each study. Hand-carried torches were used to ignite all fires. The ignition pattern in all cases was multiple-strip head fires designed to control frontal fire (fire-line) intensity. The average fire-line intensity, computed from crown scorch height (Van Wagner 1973), ranged from 630 to 2350 kW/m on the 43 plots (Table 1). Fires were conducted from May through October. The Lubrecht fires were in natural fuels in uncut stands. These fuels are representative of fuel model H (Deeming et al. 1977). The Coram, Region 1, and west Cascades fires were in partially logged stands with light to moderate slash, representative of fuel models J and K, respectively (Deeming et al. 1977).

The initial assessment of injury was made from a couple of weeks to a couple of months after the fires. This variation is not considered a problem because western larch is the only species that initiates new foliage growth shortly after burning, and these trees were observed soon after the fires. In the other species, buds are killed to nearly the same height as the foliage and there is little foliage recovery.

Data were collected on all trees within the boundaries of the experimental plots. Plot size varied from 0.12 to 9 ha (Table 1). For the Region 1 and west Cascades plots, mortality was monitored for three growing seasons following burning. Mortality was monitored during the seventh growing season at Coram and during the eighth growing season at Lubrecht. Most fire-caused mortality occurs during the first 3 years (Wagener 1961), so differences due to time since injury are assumed to have little effect on the final mortality estimates of these trees.

Binary logistic regression was used to model fire-caused mortality. The observed values of the dependent variable were 0 (live) or 1 (dead), and the probability of mortality (P_m) was estimated. A maximum likelihood fitting procedure (Bishop et al. 1975) was used to estimate the coefficients of the model. A generalized Wald (1943) statistic was used to test regression coefficients. The distribution is approximately χ^2 when the sample size is large, and is equivalent to minimizing Neyman's χ^2 (Bishop et al. 1975, pp. 348–353).

Equations were generated for the entire data set, with and without species as a categorical variable. Species was included as a categorical variable to determine if there was an additional species effect beyond that attributable to bark thickness. We assumed that published equations (Table 3) were suitable for estimating bark thickness from species and measured diameter. The independent variables were visually observed percentage of crown volume killed, computed bark thickness, transformations of these two variables, and species. The likelihood ratio was used to test for improvement in fit with the addition of species.

Predictions generated by equations with and without species were compared with each other and with the observed values. Average bias for each species was computed as the average deviation of predicted from observed values. (Species biases were 0 for the equation that included a species term.) An apparent error rate (Johnson and Wichern 1982) was computed for each equation's performance for each species. The apparent error rate is the proportion of individual trees that would be incorrectly classified as live or dead using the predicted mortality with a cutoff criterion. We used 0.5 as a cutoff (Efron 1978). All trees with P_m greater than or equal to 0.5 were classified as dead, and the rest as live. The predicted condition was then compared with the observed tree status, and an

TABLE 4. Regression coefficients, standard errors, and probability values for the two prediction equations

(A) Model 1

Effect	Coefficient	SE	Probability ($\leq$)
b_0	-1.466	0.1357	0.0001
b_1	1.910	0.1163	0.0001
b_2	-0.1775	0.0179	0.0001
b_3	-0.000541	0.000039	0.0001

(B) Model 2

Effect	Coefficient	SE	Probability ($\leq$)
b_0	-0.9245	0.1955	0.0001
DF	1.0589	0.1414	0.0001
WL	1.5475	0.2116	0.0001
ES	-1.495	0.2895	0.0001
LP	-0.1472	0.2350	0.5310
SF	-1.1269	0.2363	0.0001
RC	0.8860	0.3697	0.0165
WH	-0.7231	0.3060	0.0161
b_1	0.9407	0.1955	0.0001
b_2	-0.0690	0.0273	0.0116
b_3	-0.00542	0.000040	0.0001

NOTE: Regression coefficients: b_0, intercept; b_1, bark thickness (cm); b_2, squared bark thickness (cm^2); b_3, crown kill squared (%^{2}). Species terms: DF, Douglas-fir; WL, western larch; ES, Engelmann spruce; LP, lodgepole pine; SF, subalpine fir; RC, western red cedar; WH, western hemlock.

error recorded if the two were not in agreement. Finally, local mean deviance plots (Landwehr et al. 1984) were generated to assess the goodness of fit of the alternative equations.

Results

In the pooled data, crown volume killed (% CK) ranged from 0 to 100% and computed bark thickness (BT) ranged from 0.3 to 10.8 cm (Table 2). With some minor exceptions in species, data are well distributed throughout the ranges for both variables. Subalpine fir did not have many trees with crown kill between 25 and 75%. Trees with bark thicker than 3.0 cm are exclusively Douglas-fir or western larch. Both species are, however, well represented among the thinner-barked trees. For the other five species, bark thicker than 3.0 cm is unlikely to be found in nature.

Preliminary analysis showed that the best combination of independent variables was BT, BT^2, and % CK^2. Two equations were generated, of the form

$$P_m = 1/(1 + \exp(b_0 + \text{species term} + b_1 BT + b_2 BT^2 + b_3 \% CK^2))$$

where

P_m = estimated probability of mortality in the interval 0–1

species term = a regression coefficient to adjust for species

BT = bark thickness (cm)

% CK = percentage of the prefire crown volume killed

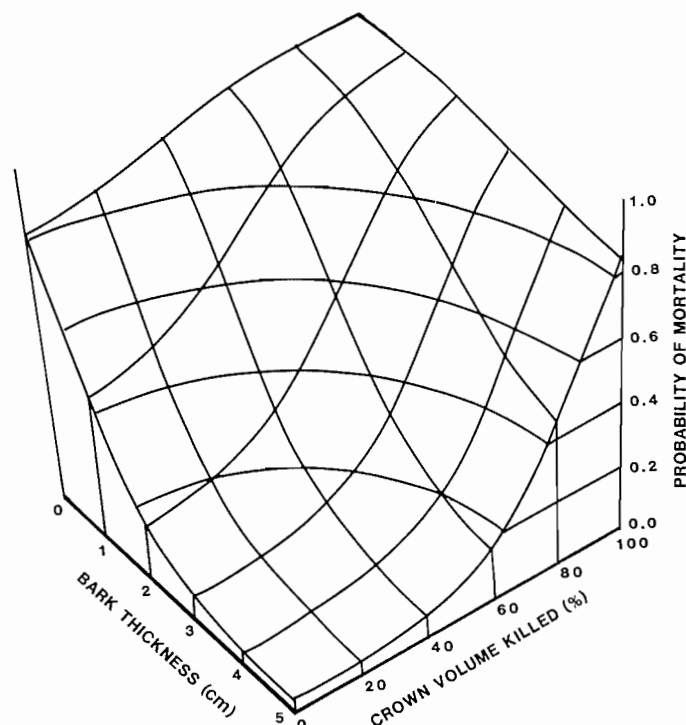b_0, b_1, b_2, and b_3 are regression coefficients

FIG. 2. Probability of mortality of seven western conifers, predicted by model 1, as a function of observed crown volume killed and bark thickness calculated from diameter at breast height (1.4 m).

In the first equation (model 1) the species term was 0 and predicted mortality was independent of species. Table 4A shows the regression coefficients, standard errors, and probability values for model 1. Figure 2 is a graphical representation of model 1. The three-dimensional response surface shows that in trees with very thin bark, predicted mortality is high, regardless of crown injury. At high levels of crown kill, predicted mortality is high even for thick-barked trees.

The second equation (model 2) has a species term for each of the seven species. This has the effect of changing the intercept, thereby shifting the response surface up or down for each species. Table 4B shows the regression estimates for this model; b_3 is virtually identical in both models, indicating that the contribution of crown injury is not strongly species dependent. In model 2, b_1 and b_2, while still significant, are closer to 0 than they are in model 1, indicating that species and bark thickness are not entirely independent. Thus, the species terms in model 2 explain some of the variability attributed to bark thickness in model 1.

The likelihood ratio test for improvement in fit with the addition of the species showed that model 2 was better than model 1 ($P \leq 0.01$). With such a large data set, however, additional variables frequently result in a formally significant improvement in fit.

The difference between the two models was further investigated by evaluating their performance (Table 5). Model 1 had very little bias in predictions of mortality for Douglas-fir, western red cedar, lodgepole pine, and western larch. Bias was 0.11 for western hemlock, indicating that the model tended to underpredict mortality by 11% for this species. Mortality of subalpine fir was also underpredicted by 15% and that of Engelmann spruce by 30%. These three species

TABLE 5. Bias and apparent error rates by species for models 1 and 2

| | n | Mean mortality rate | Bias[a] (model 1) | Apparent error rate[b] | |
				Model 1	Model 2
Douglas-fir	1488	0.202	−0.03	0.14	0.14
Western larch	287	0.157	−0.07	0.17	0.12
Engelmann spruce	96	0.875	0.30	0.49	0.12
Lodgepole pine	144	0.799	0.00	0.20	0.20
Subalpine fir	172	0.855	0.15	0.14	0.14
Western red cedar	69	0.768	−0.03	0.13	0.13
Western hemlock	100	0.870	0.11	0.18	0.11

[a]The sum of the observed minus the predicted values divided by the number of observations.
[b]The number of errors in prediction divided by the number of observations. A prediction was considered in error if it was less than 0.5 and the tree died, or if it was at least 0.5 and the tree lived.

had not only the largest positive biases but the highest observed mortalities (Table 5) and the most negative species coefficients (Table 4B). Model 2 has no species bias, as it is adjusted for species.

The models show less difference in apparent error rates (Table 5). Performance of the two models was similar in all species except Engelmann spruce. Apparent error rates for the seven species were low, ranging from 12 to 20% except in model 1 for Engelmann spruce, for which it was 49%. This implies that nearly half of the Engelmann spruce trees would have been incorrectly predicted to live or die on the basis of the 0.5 cutoff criterion.

Local mean deviance plots did not indicate systematic errors in either model. This means that while some variability is as yet unexplained by the equations, it is not due to lack of fit but rather to additional sources of variation, or to pure error.

The performance of model 1 in predicting mortality for each of the 43 sample fires is shown in Fig. 3. The observed mortality rate differed from the predicted rate by less than 0.2 for all but five fires. The average bias for the 20 fires in natural fuels was −0.07. For the 23 fires in slash fuels the average bias was −0.01 for the Coram plot, 0.08 for Region 1, and −0.02 for west Cascades.

Discussion

The species-dependent equation (model 2) resulted in minor improvements in predicted mortality compared with model 1. Although there is no species bias in model 2, the apparent error rates were comparable for all species except Engelmann spruce. The poor fit for Engelmann spruce may be related to the fact that two-thirds of these trees were sampled from two of the more severe fires. Both fires were in moderate slash fuels classified as NFDRS fuel model K (Deeming et al. 1977). These fires tended to cause little crown injury but completely girdled all but three trees.

There are a number of potential sources of variation that may affect observed mortality and model performance. These include the characteristics of the fire, the thickness and insulating properties of the bark, crown function, prefire tree vigor, and postfire insect and disease interactions.

The 43 burns encompassed a wide range of fire behavior in both natural and slash fuels. The duration of fires varies from a few seconds in light surface fuels to several hours
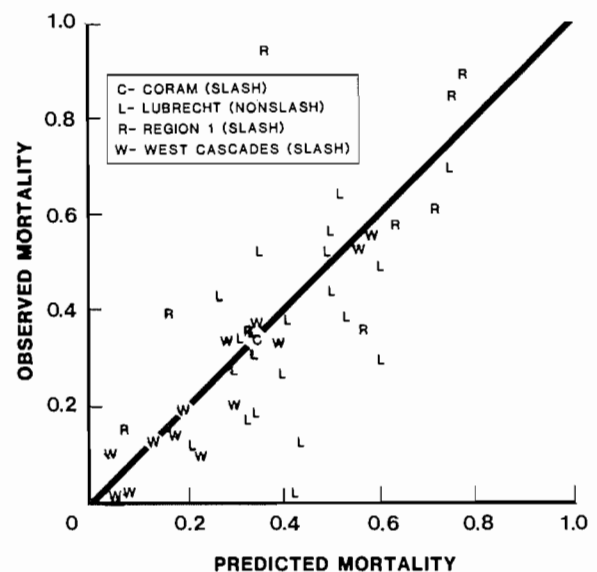

FIG. 3. Predicted versus observed probability of mortality for 43 sample fires, based on model 1.

in smoldering ground fuels (Ryan 1982). A variable that accounted for differences in fire characteristics might improve the prediction of mortality. However, there were not enough data to stratify by fire behavior, fuel model, or fuel moisture regime.

Model 1 appeared to perform equally well in slash and natural fuels. The slash fire for which model 1 performed particularly poorly (Fig. 3) was a pure stand of Engelmann spruce which suffered extensive cambium injury but little crown injury. The two nonslash fires for which model 1 performed most poorly were marginal spring fires in natural fuels. These fires did not cover the treatment areas uniformly, and many trees received no bole scorch.

Between the nonslash and slash areas there were no consistent differences in injury or mortality that could be ascribed to fuel or fire behavior. The height of crown scorch is determined by fire-line intensity, wind speed, and air temperature (Van Wagner 1973). Girdling, however, depends on both the heat received and the insulating capacity of the bark. Slash fuels are often burned under somewhat wetter conditions than natural fuels, and ignition of slash fuels is often more stringently controlled. The net result is that while there is a greater potential for bole heating in slash fires, the

available fuel and the heat load received by trees are often not substantially different in slash and nonslash fires.

Actual measured cambium injury would undoubtedly be a better predictor of tree mortality than bark thickness. Thermal diffusion theory suggests that both the thickness and insulating efficiency of the bark, as well as the temperature and duration of a fire, influence cambium mortality. The bark thickness equations (Table 3) may not adequately reflect the true bark thicknesses of our trees because bark thickness to diameter ratios vary somewhat according to site and ecotype. Thermal diffusivity, a measure of insulating efficiency, may also vary with age, particularly for a species such as Douglas-fir which has a high percentage of cork in the bark of older trees. Diffusivity differences are not, however, expected to be nearly as important as differences in bark thickness. Evidence to support this contention is found in heat transfer studies (Martin 1963; Reifsnyder et al. 1967) that demonstrate that the time required for a lethal heat pulse to reach the cambium increases linearly with thermal diffusivity but with the square of bark thickness. Laboratory studies have found slight (Martin 1963) to 2-fold (Reifsnyder et al. 1967) differences in thermal diffusivity of coniferous bark. By contrast, there is a 40-fold range in the computed bark thickness in these data.

Although bark thickness does not reflect the variations in bark thermal properties and fire duration that probably influence cambial injury, it is a more readily available predictor than cambial injury itself. Its performance as a predictive variable was good.

In model 1 we assume that all species and sizes respond similarly to a given proportion of crown volume killed. This is probably not strictly true. Patterns of carbon allocation change with age and vary between species. The effects of bud kill and defoliation by fire are also likely to vary with age and species. Within species these interactions may have been partially accounted for because bark thickness is positively correlated with age.

Based on external evidence (e.g., Ryan 1982; Ryan et al. 1988) we expect the models to slightly underestimate mortality of trees with bark thicker than 3.0 cm and crown kill approaching 100%. In these data few Douglas-fir and western larch trees larger than 60 cm DBH received extensive crown scorch. Contrary to the curve shown in Fig. 2, we would expect complete mortality at 100% crown kill (foliage and buds), regardless of bark thickness. We chose not to force the model to fit the perceived condition that all trees with 100% crown kill will die, because of the difficulty of fitting the model and interpreting the statistics. Also, there are few applications in which the predicted mortality at 100% crown kill will deviate far enough from unity to have any practical significance.

Prefire tree vigor is generally considered to affect survival following fire injury, particularly crown kill (Ryan 1982). Trees with sparse foliage are not likely to maintain a positive carbon balance if much leaf area is lost. In this study there was no adequate or consistent measure of tree vigor to use in modeling mortality.

Fire-injured trees often succumb to insect attack or disease. Whether these are opportunistic attacks on mortally injured trees or are direct causes of mortality is usually not clear. Trees were extensively attacked by bark beetles (Dendroctonus spp.) on at least one area in both the west

Cascades and Region 1 plots. Fruiting bodies of the pouch fungus (Polyporous volvatus) were found extensively on the Douglas-fir trees in one Region 1 stand. Whether these were related to undetected injury or local insect and disease conditions is unknown. Insect and disease attacks appeared to occur on an individual tree basis in other areas. As insects and diseases were present on many trees, these postfire interactions are inherent in the models' mortality predictions.

Despite these additional sources of variation, performance was good, and these equations should be useful in managing fire-injured stands. Bark thickness and crown kill alone gave enough information to predict correctly the status of at least 80% of the trees of all species except Engelmann spruce, and to estimate stand mortality within 20% accuracy for 88% of the stands sampled. Comparison of the two models suggests that most of the differences in mortality between species are due to differences in bark thickness.

The models have several potential applications. They may be used in the process of developing silvicultural prescriptions to assess the feasibility of using prescribed fire for site preparation (Reinhardt and Ryan 1988). They can be used following fire, either to assess the probability of mortality of individual trees when developing salvage guidelines, or to assess potential stand mortality when considering management alternatives.

Although data from trees burned in wildfires were not included in this study, we feel that the equations are potentially useful for salvage marking all fire-injured stands of the represented species. Mortality is determined by the type and degree of injury received. Median fire characteristics and injuries may differ between wildfires and prescribed fires but injury from wildfires is not likely to occur beyond the range of injury in this study. Thick-barked trees are most frequently killed by crown injury, whereas thin-barked trees may be killed by either crown or cambial injury.

Crown scorch increases with fire-line intensity (Van Wagner 1973). In wildfires, fire-line intensity is constrained only by the prevailing fuel and environmental conditions. As a result, extensive crown injury is common. In prescribed fires, managers select weather and fuel moisture conditions and modify ignition patterns to control fire-line intensity, often specifically to achieve an acceptable level of crown scorch. The equations predict high mortality at high levels of crown scorch, so they should be applicable for wildfires.

Cambium injury is more closely related to the duration of burning than it is to fire-line intensity. Although the factors controlling the duration of flaming and glowing combustion are not well defined, the size of the fuel, its arrangement, and its moisture content appear important. Prescribed fires burning under the same fuel and weather conditions as a wildfire would likely have the same effect on cambium. Thick-barked trees may be girdled by smoldering ground fires in deep, dry duff and, less frequently, by burnout of woody fuels. Woody fuel burnout rarely results in complete girdling of thick-barked trees because fine surface fuels burn out too quickly to cause injury, while longer-burning coarse fuels occupy too little of the total planform area to be frequently found in juxtaposition with tree boles, even in partially logged stands. If only light, fine fuels are present, the duration of burning will be short, and the contribution of bark thickness to fire resistance can be expected to be less of a factor in tree survival than is crown injury. Some of the 43 plots contained dry duff which was mostly consumed,

resulting in basal girdling of thick-barked trees. Thus, fire injuries to these trees are similar to those often encountered in wildfires.

Conclusions

The logistic regression equations have not been tested against independent data, so they should be viewed as preliminary. They are, however, based on a large set of data and encompass most of the fuel and environmental conditions in which managers apply fire beneath standing trees. We believe they are widely applicable. They rely on readily accessible data, and are applicable over a wide range of tree sizes and fire injuries and in a variety of stand conditions. The equations should prove useful to managers making post-fire decisions for mixed conifer stands in the northwest.

The equation based on the independent variables bark thickness, squared bark thickness, and percent crown kill (model 1) explained much of the variation in the observed mortality for the seven species. Although diameter to bark thickness ratios were assumed, and tree vigor and fire behavior were not quantified, model 1 correctly predicted the status of between 80 and 87% of the trees of all species except Engelmann spruce. The species-dependent equation (model 2) performed slightly better than model 1 for western larch and western hemlock, and considerably better for Engelmann spruce. If these species are a concern, model 2 is preferable to model 1.

Knowledge of the effects of fire on trees is valuable both for controlling fire injury and for predicting its consequences. Additional studies are needed to quantify the physical relationships between fire behavior and the tree characteristics that lead to fire injury. Better methods for quantifying fire injury and interpreting its physiological consequences would improve our ability to predict tree mortality.

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